Abstract – High frequency ultrasound (HFUS) and intravascular ultrasound (IVUS) based elastography can be utilized for tissue elasticity imaging at a microscopic level. Mechanical strain fields inside the tissue are calculated as the spatial derivatives of estimated displacement fields. In this paper, a technique for the estimation of 2D displacement fields is presented. Axial and lateral displacements in the imaging plane are estimated by tracking speckle in B-mode images and analyzing phase differences between image spectra. Concept and limitations of the proposed approach are discussed. Results are compared with an approach for 1D axial displacement estimation, which is based on the analysis of radio frequency (rf) echo signals. The implemented techniques were applied to assess skin elasticity and to analyze non-uniform rotational distortions (NURD) in IVUS with rotating single element transducers. Results of in vivo measurements are presented. It is shown that B-mode based strain imaging is feasible provided that applied strains are sufficiently small to prevent decorrelation of echo signals.

INTRODUCTION

HFUS and IVUS enable high resolution imaging of tissues for applications in dermatology, ophthalmology and imaging of coronary arteries. Besides morphological imaging, HFUS and IVUS based elastography for the assessment of elastic tissue properties are of great interest because vulnerable coronary plaques show mechanical properties different from those of calcified plaques. In bent rotating single element catheters, however, non-uniform rotational distortions (NURD) have to be taken into account as an artifact when analyzing consecutive frames of acquired echo signals. The proposed 2D speckle tracking approach was utilized to estimate frame to frame displacements caused by NURD.

strain imaging of skin

We have already previously reported about our 20 MHz ultrasound skin elastography system, which is based on the suction method [2,3].

echo signal acquisition

In this setup, the pressure inside a vacuum chamber at the skin surface is stepwise decreased, causing suction and, thus, mainly axial displacements of the layered skin, see Fig. 1:

![Fig. 1: HFUS skin elasticity imaging system](image)

After each pressure change, frames of rf echo signals are acquired performing a mechanical scan with a spherically focused single element transducer (44 µm / 139 µm axial / lateral resolution). A pressure control system was implemented for reproducible conditions.

strain estimation

Although it is intended to cause mainly axial elevations of the skin in sound propagation direction $z$ with the suction system, lateral and elevational displace-
ments in lateral direction $x$ and elevational direction $y$ are given as well. Furthermore, because of the complicated skin deformation, in general elongations as well as compressions can occur in all directions. Therefore, we propose to consider positive and negative displacements in the signal processing. For the assessment of local strains inside the tissue, the skin surface is segmented and the echo signals are aligned relative to the segmented contours first. In Fig. 2, a B-mode image, reconstructed from one frame of acquired rf echo signals, acquired at a burn scar, and the segmented skin surface are shown:

![Fig. 2: B-mode image and segmented skin surface: Burn scar (left), healthy skin (right)](image)

The segmentation of skin surfaces is performed in each of the echo signal frames, which are acquired at decreased pressures $p$, see Fig. 3:

![Fig. 3: Contours plot: Segmented skin surfaces in consecutively acquired echo signal frames](image)

Because the muscle tissue underneath the skin and the subcutaneous fat can be assumed to remain effectively in its initial position, the contours plot already depicts the ‘overall’ mechanical properties of the imaged skin areas. Skin surface elevation is large in the healthy skin, whereas it is significantly smaller in the scar. For spatially resolved imaging of mechanical strains over depth inside the skin, acquired rf echo signals are aligned relative to the segmented contours and B-mode images are recalculated. Displacements between consecutively acquired frames of B-mode images and rf echo signals, respectively, are estimated in adjacent windows over depth, starting from the skin surface, see Fig. 4:

![Fig. 4: Aligned B-mode images, adjacent windows](image)

Estimated displacements in consecutive windows are accumulated over depth, and axial and lateral strains are then estimated determining the slopes of linear regression fits of the accumulated displacements over spatial coordinates $z$ and $x$ [2,3].

### NURD in IVUS Systems

Friction forces in bent IVUS catheters often cause non-uniform transducer rotations with non-constant angular velocity inside the catheter shaft. As a result, consecutively acquired A-lines show angular displacements along the circumference of the transducer between each other. Measurements were performed with a Galaxy IVUS scanner (Boston Scientific Inc., Natick, MA, USA) with a 40 MHz rotating single element catheter. In Fig. 5, a B-mode image, acquired at a speckle phantom, is shown:

![Fig. 5: IVUS imaging system (left); IVUS B-mode image: Speckle phantom (right)](image)

### Estimation of Displacement Field

In this section, the utilized approach for estimation of 2D axial and lateral displacements by speckle
tracking in B-mode images and the 1D axial displacement estimation approach, based on cross correlation of analytical rf echo signals, are introduced.

2D Speckle Tracking Approach

Speckle, which is inherent in the B-mode images, is tracked in the imaging plane. Axial and lateral displacements \( \Delta z \) and \( \Delta x \) between two consecutive B-mode images \( b_1(z,x) \) and \( b_2(z,x) \) are estimated analyzing the corresponding image spectra \( B_1(\omega_z,\omega_x) \) and \( B_2(\omega_z,\omega_x) \). Displacements result in a phase difference \( \Delta \phi \) between the two spectra, which is a linear function of spatial frequencies \( \omega_z \) and \( \omega_x \). Estimates are obtained fitting a 2D linear function to the measured phase differences, whereby only spectral components with sufficiently large energy are taken into account for reasonable phase information \([3]\):

\[
\sum_v (\Delta \phi_v - (\omega_{z,v} \cdot \Delta z^2 + \omega_{x,v} \cdot \Delta x)) \overset{2}{=} \text{min},
\]

with:

\[
|B_{1,2}(\omega_{z,v},\omega_{x,v})| \geq B_{\text{threshold}}
\]

For unambiguous phase information \( \Delta \phi \), displacements must not exceed axial sampling interval \( \Delta z \) and lateral A-line spacing \( \Delta x \):

\[
\Delta \phi_{\text{max}} = \pm 180^\circ \Rightarrow |\Delta z| \leq \frac{1}{\Delta z_{\text{shift}}}, |\Delta x| \leq \frac{1}{\Delta x_{\text{shift}}},
\]

(2)

Strains, which are spatial derivatives of estimated displacements, must be restricted. Differences of accumulated displacements \( \Delta z' \) and \( \Delta x' \) in adjacent windows over the window shifts must be limited:

\[
|\varepsilon_z| = \frac{\Delta z'}{\Delta z_{\text{shift}}} \leq \frac{1}{\Delta z_{\text{shift}}}, |\varepsilon_x| = \frac{\Delta x'}{\Delta x_{\text{shift}}} \leq \frac{1}{\Delta x_{\text{shift}}},
\]

(3)

To validate the reliability of displacement estimates, we calculate the correlation coefficient of B-mode images, compensated for estimated displacements in each window. Only strain estimates with correlation coefficients \( \rho > 90\% \) are displayed \([2,3]\).

1D Axial Cross Correlation Approach

In a second approach, axial displacements are estimated correlating analytical rf echo signals. Axial displacements between A-lines in consecutive echo signal frames result in a phase shift of the complex correlation function. The zero of the phase is iteratively searched, which results in a very efficient approach (`phase root seeking`) \([5]\). Here, like in the 2D speckle tracking approach, we calculate the correlation coefficient as a measure of the reliability of displacement estimates.

**Measurements**

In vivo measurements were performed on healthy skin, burn scars and nevi. B-mode images and strain images, which were obtained using the above discussed approaches, are presented. Furthermore, NURD in IVUS echo signals, acquired at a speckle phantom, was analyzed.

**Strain Imaging of Skin**

Fig. 6 shows a B-mode image and estimated axial and lateral strains of a burn scar and healthy skin:

![Image](image-url)

Fig. 6: Burn scar (left) / healthy skin (right):

a) B-mode image; b) Axial strain (1D approach);

c) Axial and lateral strains (2D approach)

Positive strains denote elongations, whereas negative strains denote compressions. Estimates for the axial strain \( \varepsilon_z \), obtained with the two approaches are in a good mutual agreement. It can be seen that strong axial elongations occur on the subcutaneous fat and in the burn scar. In the healthy skin, on the other hand, strains are small. Lateral strains are also asymmetric, and large lateral compressions are found in the healthy skin. These findings can be explained by the disarrangement of elastic and collagen fibers in the burn scar. In Fig. 7, strain images of a nevus are shown. It can be seen that the elastic properties of the nevus are significantly different from elasticity of the surrounding dermis. Strong compressions are given in the nevus, whereas the strains in the surrounding dermis are very small. Again, large elongations are
found in the subcutaneous fat. In lateral direction mainly elongations occur:

Analysis of NURD in IVUS

Frames of IVUS B-mode images were analyzed, transferring images from given Cartesian coordinates to cylindrical coordinates with radius $R$ and circumferential angle $\varphi$, see Fig. 8a):

NURD causes displacements in angular direction $\varphi$, which is apparent in Fig. 8b). Circumferential displacements were estimated with sub-sample resolution utilizing the above introduced speckle tracking approach. Reasonable results with constant displacements over radius are obtained for each line.

SUMMARY AND CONCLUSIONS

In this paper, an approach for estimation of 2D displacement field in the imaging plane, based on the analysis of B-mode image spectra, was introduced. Furthermore, an approach for 1D axial displacement estimation, correlating analytical rf echo signals, was discussed. It was shown, that high resolution strain imaging is feasible with these two approaches. We propose to consider positive as well as negative displacements and strains in signal analysis, and to calculate the cross correlation coefficients of consecutive B-mode images and echo signals, compensated for estimated displacements, as measures for the reliability of estimated displacements. Results of in vivo measurements were presented, showing that the implemented HFUS skin elasticity imaging system allows to image mechanical skin properties over depth. The proposed speckle tracking technique was furthermore applied to analyze NURD, which is an artifact in IVUS imaging with rotating single element transducers. In our future work, we are going to utilize this information to compensate for angular displacements from frame to frame. This will be a pre-processing to ensure a high correlation of A-lines for further analysis in IVUS strain imaging.

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